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The comparison of two models that determine the effects of a vegetation canopy on passive microwave emission

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Abstract

Two contrasting models are used to account for the effects of vegetation on microwave emission from the soil. These are: a simple model which requires two empirically derived parameters as input data (optical depth and single scattering albedo); and a complex discrete model which requires a detailed description of all of the components of the vegetation canopy. Both models account effectively for the vegetation, although the simple model takes a fraction of the computation time compared to the discrete model. However, the simple model was fitted to the data, whereas the discrete model used measured parameters as input. In addition to predicting the microwave brightness temperature, the discrete model also calculates the optical depth and single scattering albedo. These calculated values were in agreement with those fitted using the simple model. Therefore, it is suggested that the discrete model could be used to calculate the input parameters for the simple model.

Introduction

An L-band (21 cm, 1.4 GHz) passive microwave radiometer measures the intensity of the microwave emission from the land surface in terms of a brightness temperature. This brightness temperature is related to the surface soil moisture (Schmugge *et al.*, 1986 and Jackson *et al.*, 1995). Any vegetation that is present is usually treated as noise and its effect is estimated using a single parameter proportional to the vegetation water content (Jackson, 1993). The constant of proportionality is generally obtained from previous data sets (Jackson and Schmugge, 1991). This method of accounting for the vegetation is not accurate enough when modelling the microwave emission detected by the radiometer, e.g. when using time courses of modelled microwave brightness temperature in the estimation of soil hydraulic properties (Burke *et al.*, 1997a, 1998).

This paper examines two of the vegetation canopy models reviewed by Kerr and Wigneron (1994). The first is a simple two parameter model (Ulaby *et al.*, 1986) which requires little computing power but uses empirically derived input parameters, the single scattering albedo and the optical depth. The second is a complex discrete model (Wigneron *et al.*, 1993) which uses measurements of the vegetation canopy as input data, but requires significant computing time. However, the complex discrete model can be used to calculate values of the single scattering albedo and the optical depth required as input to the simple model.

Modelling background

A vegetation canopy will scatter and absorb microwave emission from the soil. It will also contribute with its own emission, which will be scattered and absorbed by the canopy through which it passes. The radiative transfer equations (Eqns. 1 and 2) represent the radiation balance at horizontal polarisation within an infinitesimal volume of the canopy. The energy balance for upward radiative transfer is:

$$\mu \frac{dT_{Bh}(\theta,z)}{dz} = K_a T_{can}(z) - K_e(\theta) T_{Bh}(\theta,z) + \int_{-1}^{1} \left((h,h') T_{Bh}(\theta',z) + (h,v') T_{Bv}(\theta',z) \right) d\mu' \quad (1)$$

The energy balance for downward radiative transfer is:

$$-\mu \frac{dT_{Bh}(\pi-\theta,z)}{dz} = K_a T_{can}(z) - K_e(\pi-\theta)T_{Bh}(\pi-\theta,z) + \int_{-1}^{1}\left((h(\pi-\theta),h')T_{Bh}(\theta',z) + (h(\pi-\theta),v')T_{Bv}(\theta',z)\right)d\mu' \quad (2)$$

where T_{Bh} is the horizontally polarised microwave brightness temperature (K), T_{can} is the physical temperature of the canopy (K), z is the depth within the canopy (m), K_a is the absorption coefficient, K_s is the scattering coefficient, K_e ($=K_a+K_s$) is the extinction coefficient, θ, θ' are incidence angles with $\mu = \cos\theta$ and $\mu' = \cos\theta'$ and (h,h'), (h,v') are scattering phase functions, where (p,q') represents the scattering probability of p polarised radiation being scattered into q polarised radiation (p and q represent horizontally (h) and vertically (v) polarised radiation interchangeably). The first term in the equations is the Source Function which describes the thermal emission from the canopy, the second term represents the radiation absorbed by the canopy and the final term represents the scattering by the vegetation.

There are no analytical solutions to Eqns. 1 and 2. However, they can be solved numerically (complex discrete model, Wigneron *et al.*, 1993) or simplified by assuming that the scattering effects, and hence the phase functions, are negligible (simple model, Ulaby *et al.*, 1986). The simple model is only valid at longer wavelengths where the dimensions within the canopy are of the same order of magnitude as the wavelength of detection.

The brightness temperature at the radiometer determined using the simple model is given by the sum of the emission from the soil, the upward emission from the canopy, and the downward emission from the canopy reflected by the soil. Any vegetation it passes through attenuates this microwave emission. The simple model is given by:

$$T_B = \Gamma T_{BSoil} + (1-\Gamma)(1-\Omega)T_{can} + (1-\Gamma)(1-\Omega)\Gamma T_{can} r_s \quad (3)$$

$$\Gamma = e^{-\tau \sec\theta} \quad (4)$$

$$\tau = K_e d \quad (5)$$

$$\Omega = \frac{K_s}{K_e} \quad (6)$$

where T_{Bsoil} is the brightness temperature emitted by the soil, r_s the reflectivity of the soil surface, the optical depth, d the canopy height and the single scattering albedo.

The optical depth determines the amount of absorption and emission by the canopy and is commonly defined by:

$$\tau = \beta\theta_{veg} \quad (7)$$

where θ_{veg} is the vegetation water content and β is an empirically derived constant, dependent mainly on the canopy structure and the polarisation and wavelength of detection (Jackson and Schmugge, 1991). The single scattering albedo determines the distribution of absorption and emission within the canopy. It is close to zero and has frequently been assumed to be zero (Jackson and Schmugge, 1991). There are very few examples where Ω has been estimated (Kerr and Wigneron, 1993) and its dependence on vegetation characteristics is unknown.

The advantage of the discrete model over the simple model is that it requires no empirically derived input parameters. It uses a numerical solution of Eqns. 1 and 2 and estimates the scattering phase functions and the absorption and scattering coefficients from measurements of the vegetation characteristics shown in Table 4: the leaves are represented by discs and the stems are represented by finite cylinders (Wigneron *et al.*, 1993). The optical depth and the single scattering albedo are calculated from the extinction and absorption coefficients (Eqns. 5 and 6).

Materials and methods

EXPERIMENTAL DATA

The models were run for a soybean canopy that was monitored during a 1985 field experiment carried out at the United States Department of Agriculture (USDA), Beltsville Agriculture Research Center. These data were analysed by Burke et al. (1998) and are described in detail by Burke (1997). The crop was grown on three different soils and intensively monitored during three drying periods. Results discussed here are for two of these combinations: soybeans aged between 56–65 days old (dry down 2) and grown on a sandy loam soil; and soybeans aged between 97–113 days old and grown on a loam soil (dry down 3). There was 100% canopy cover for both of these periods; however the crop had begun to senesce by the beginning of dry down 3. The L band microwave brightness temperature at 10° from nadir was recorded approximately three times a day. The plant height and the wet and dry biomass of the canopy were also measured. However, the additional parameters required by the discrete model were not measured but obtained from Wigneron (1993), who monitored a similar soybean canopy.

MODEL DESCRIPTION

The vegetation models were run in conjunction with MICRO-SWEAT, a soil water and energy budget model (SWEAT, Daamen and Simmonds, 1996) coupled with a microwave emission model (Wilheit, 1978). MICRO-SWEAT was developed by Burke *et al.* (1997a, 1998) who used the model to predict time courses of microwave brightness temperature during a drying cycle. Both vegetation models were linked to MICRO-SWEAT via the microwave emissivity of the soil-canopy interface (Fig. 1). The input parameters required by SWEAT were set to the

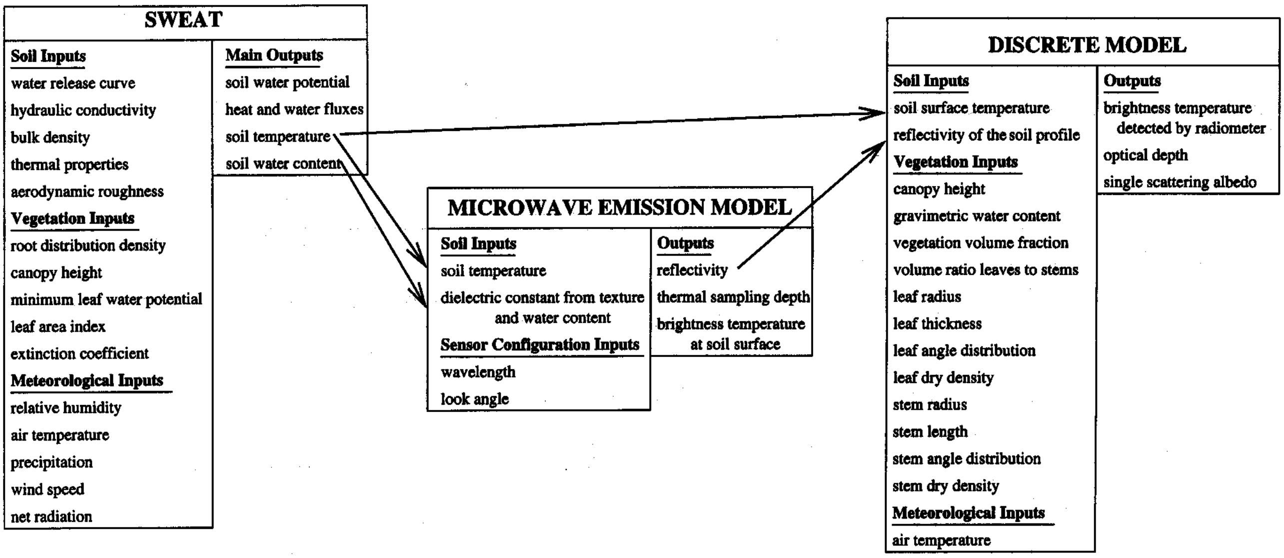

Fig. 1. *Principal input and output data for all of the models discussed in this paper.*

measured data (meteorological), estimated data (vegetation) or fitted data (soil hydraulic properties, Burke *et al.*, 1998).

Results and discussion

Figures 2 (dry down 2) and 3 (dry down 3) show time courses of the microwave brightness temperature from both the simple and discrete models, along with the measured data. All of the parameters required by the discrete model were set to either their estimated (Wigneron, 1993) or measured values. In the case of the simple model, Ω was set to zero and τ fitted. The root mean square error (*RMSE*) and bias between the modelled and the measured brightness temperatures (Table 1) were calculated for the periods DOY 214 on (dry down 2) and DOY 255 on (dry down 3). Earlier time periods were not used because of uncertainties in the timing of the rain events. The *RMSE* for both of the models was within the acceptable error of 5 K (Burke *et al.*, 1998). The following sections address the two models separately, compare the results and then discuss a possible method for determining the vegetation effects on the microwave emission.

SIMPLE MODEL

The values of the single scattering albedo (Ω) and optical depth (τ) were unknown. Initially they were both adjusted systematically within the range of possible values to find the best-fit between the measured and modelled brightness temperature. However, no unique pair of values defined a 'best-fit'; instead it was represented by a series of different combinations (Table 2 for Fig. 2). At lower τ the model was sensitive to τ and not very sensitive to Ω, whereas at higher τ the *RMSE* increases slightly and the model becomes more sensitive to Ω and less sensitive to τ. It is suggested that, for the younger soybean canopy shown in Table 2, τ is between 0.3 and 0.5 and Ω is between 0 and 0.09. Similar results were obtained for the older soybean canopy with τ between 0.45 and 0.65 and Ω between 0 and 0.1.

A more precise evaluation of τ can be obtained by setting Ω to zero (Jackson and Schmugge, 1991) and fitting τ. Table 3 compares the fitted values of τ ($\Omega = 0$) to those derived using Eqn. 7 with $\beta = 0.086$ (defined for a soybean canopy by Jackson and O'Neill, 1991) and $\beta = 0.15$ (defined for agricultural crops by Jackson and Schmugge, 1991). Interestingly, the fitted values of τ agree with different derived values: for dry down 2, $\beta = 0.15$ produces

Table 1. RMSE between modelled and measured brightness temperature calculated for the two different models.

	dry down 2		dry down 3	
	RMSE (K)	bias (K)	*RMSE* (K)	bias (K)
discrete model	3.8	1.7	2.0	–0.7
simple model	2.0	–0.1	2.6	–0.1

Table 2. RMSE between modelled and measured brightness temperature for different combinations of the optical depth and single scattering albedo.

		single scattering albedo												
		0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12
	0.3	10.2	11.1	11.9	12.8	13.7	14.6	15.5	16.3	17.2	18.1	19.0	19.9	20.8
	0.4	3.6	4.6	5.7	6.7	7.8	8.9	10.0	11.1	12.2	13.3	14.4	15.5	16.6
	0.5	3.0	2.2	1.8	2.3	3.3	4.5	5.7	7.0	8.2	9.5	10.8	12.1	13.4
	0.6	7.3	5.9	4.5	3.2	2.2	1.9	2.6	3.8	5.2	6.6	8.0	9.5	11.0
	0.7	10.9	9.3	7.7	6.1	4.6	3.2	2.1	2.0	3.0	4.4	5.9	7.5	9.1
	0.8	13.9	12.2	10.4	8.7	7.0	5.3	3.7	2.4	2.0	2.9	4.4	6.0	7.7
optical	0.9	16.4	14.5	12.7	10.8	8.9	7.1	5.3	3.6	2.3	2.2	3.3	5.0	6.7
depth	1	18.4	16.4	14.4	12.5	10.5	8.6	6.6	4.8	3.1	2.1	2.7	4.2	6.1
	1.1	20.0	18.0	15.9	13.8	11.8	9.7	7.7	5.7	3.8	2.4	2.3	3.7	5.6
	1.2	21.4	19.2	17.1	14.9	12.8	10.6	8.5	6.4	4.4	2.8	2.2	3.4	5.3
	1.3	22.5	20.2	18.0	15.8	13.5	11.3	9.1	7.0	4.9	3.1	2.2	3.2	5.1
	1.4	23.4	21.1	18.8	16.5	14.2	11.9	9.6	7.4	5.2	3.3	2.2	3.2	5.0
	1.5	24.1	21.7	19.4	17.0	14.7	12.3	10.0	7.7	5.5	3.5	2.3	3.1	5.0
	1.6	24.7	22.3	19.8	17.4	15.0	12.6	10.3	7.9	5.6	3.6	2.3	3.1	5.1

the best results, whereas for dry down 3, $\beta = 0.087$ is better. These results are consistent with those found by Wigneron *et al.* (1996) who obtained $\beta = 0.125$ for green vegetation and $\beta = 0.04$ for a senescent crop just before harvest. The crop had only just begun to senesce at the beginning of dry down 3.

DISCRETE MODEL

The input data required for the discrete model (Fig. 1) were set to the values shown in Table 4. An estimate of the vegetation volume fraction was obtained by calculating the volume occupied by the water in the canopy using the assumption that water is incompressible. The differences in the input data for dry down 3 compared to dry down 2 are an increased plant height and vegetation volume fraction and a decreased vegetation water content (g g^{-1}). The onset of senescence results in this decrease in water content. The optical depths calculated by the discrete model are shown in Table 3 and the single scattering albedos were found to be 0.085 (dry down 2) and 0.054 (dry down 3). This decrease in single scattering albedo between dry downs 2 and 3 is also due to the onset of senescence between the two drying periods.

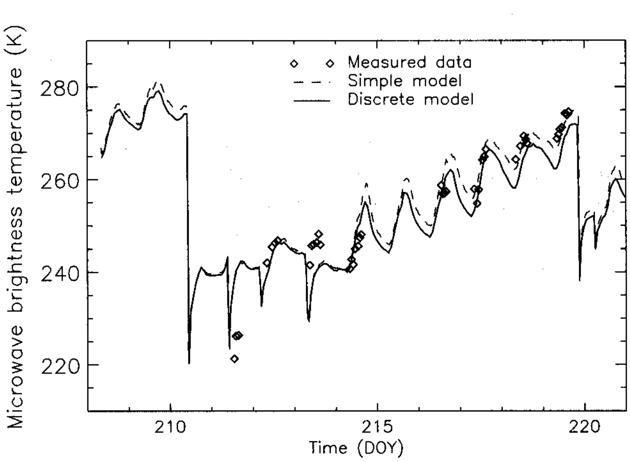

Fig. 2. *Time course of microwave brightness temperature for dry down 2.*

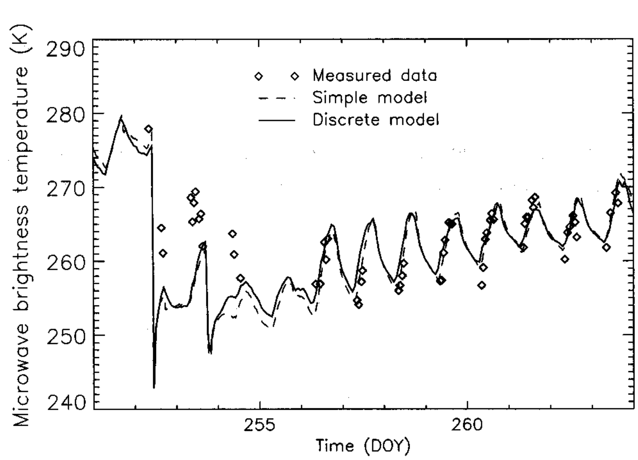

Fig. 3. *Time course of microwave brightness temperature for dry down 3.*

Table 3. Values of the optical depth derived in four different ways.

	dry down 2	dry down 3
SIMPLE MODEL		
fitted optical depth (= 0)		
(range of acceptable values (RMSE < 5 K)	0.33	0.45
	0.31–0.39	0.44–0.52
DISCRETE MODEL		
calculated optical depth	0.36	0.49
EMPIRICAL DERIVATION ($\tau = \beta\theta_{veg}$)	0.21	0.46
derived optical depth (= 0.086)	0.36	0.81
derived optical depth (= 0.15)		

Table 4. Input parameters required for the discrete model.

input parameter	dry down 2	dry down 3
canopy height (m)	0.8	1.15
gravimetric water content (g g^{-1})	0.84	0.75
total vegetation volume fraction	0.003	0.004
volume ratio, leaves to stems	1	1
leaf half thickness (m)	0.0001	0.0001
leaf radius (m)	0.032	0.032
leaf angle distribution	$p(\beta) = \cos(\pi/2(\beta-30)/(90-30))$ orientations between 0 and 90°	$p(\beta) = \cos(\pi/2(\beta-30)/(90-30))$ orientations between 0 and 90°
leaf dry density (g cm^{-3})	0.2	0.2
stem radius (m)	0.0015	0.0015
stem half length (m)	0.05	0.05
stem angle distribution	uniform distribution with possible orientations between 65 and 75	uniform distribution with possible orientations between 65 and 75
stem dry density (g cm^{-3})	0.4	0.4

MODEL COMPARISON

There is no apparent difference between the performance of the two models either visibly (Figs 2 and 3) or in terms of the calculated errors (Table 2). The values of τ calculated by the discrete model are in good agreement with the values fitted using the simple model and $\Omega = 0$ (Table 2); likewise the values of Ω fall within the ranges discussed above. If the values of τ and Ω from the discrete model were used as input data to the simple model, the RMSE would be 5.0 K for dry down 2 and 4.8 K for dry down 3. These errors fall within the acceptable limit of 5 K (Burke *et al.*, 1998). Therefore, estimates of the single scattering albedo and optical depth from the discrete model could be used as input data to the simple model.

Concluding remarks

The discrete and simple models both estimate the time courses of microwave brightness temperature over a drying period to within the required accuracy. However, the input parameters required by the simple model, the single scattering albedo (Ω) and the optical depth (τ) are usually derived empirically. In the two examples studied here, Ω was set to zero and derived from the 'best-fit' between modelled and τ measured data.

The discrete model requires a large number of parameters all of which can be measured. It can also be used to calculate values of the single scattering albedo and the optical depth. The discrete model could be used on a one-off basis to obtain values of Ω and τ from purely measured data. Their values could then be input into the simple model, which is less computationally expensive to run.

The work discussed here is a preliminary study of the feasibility of the use of such a method to provide input parameters for a simple vegetation model. A more complete set of vegetation parameters is required for a robust analysis. In the future, optical remotely sensed data may be incorporated to provide estimates of some of the parameters required as input to the discrete model (Burke *et al.*, 1997b).

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References

Burke, E.J., Gurney, R.J., Simmonds L.P. and O'Neill, P.E., 1998. Using a modelling approach to predict soil hydraulic properties from passive microwave measurements. *IEEE Geosci. Remote Sens.*, **GE-36**, 454–462.

Burke, E.J., Gurney, R.J., Simmonds, L.P. and Jackson, T.J., 1997a. Calibrating a soil water and energy budget model with remotely sensed data to obtain quantitative information about the soil. *Wat. Resour. Res.*, 33, 1689–1697.

Burke, E.J., Banks, A.C. and Gurney, R.J., 1997b. Remote sensing of soil-vegetation-atmosphere transfer processes. *Progr. Phys. Geog.*, **21**, 549-572.

Burke, E.J., 1997. Using a modelling approach to predict soil hydraulic parameters from passive microwave measurements for both bare and cropped soils. PhD Thesis, University of Reading, UK.

Kerr, Y.H., and Wigneron, J.-P., 1994. Vegetation models and Observations—A review. *ESA/NASA International workshop on Passive Microwave Remote Sensing Research Related to Land-Atmosphere Interactions*, Eds. B.J. Choudhury, Y.H. Kerr, E.G. Njoku and P. Pampaloni, 317–344.

Jackson, T.J., 1993. Measuring surface soil-moisture using passive microwave remote-sensing. *Hydrol. Processes*, **7**, 139–152.

Jackson, T.J., Le Vine, D.M. Schmugge, T.J. and Schiebe, F.R., 1995. Large area mapping of soil moisture using the ESTAR passive microwave radiometer in Washita'92. *Remote Sens. Environ.*, **53**, 27–37.

Jackson, T.J., and O'Neill, P.E., 1990. Attenuation of soil microwave emission by corn and soybeans at 1.4 and 5 GHz. *IEEE Trans. Geosci. Remote Sens.*, **GE-28**, 978–980.

Jackson, T.J. and Schmugge, T.J., 1991. Vegetation effects on the microwave emission of soils. *Remote Sens. Environ.*, **36**, 203–212.

Schmugge, T.J., O'Neill, P.E. and Wang, J.R., 1986. Passive soil moisture research. *IEEE Trans. Geosci. Remote Sens.*, **GE-24**, 12–22.

Ulaby, F.T., Moore, R.K. and Fung, A.K., 1986. *Microwave Remote Sensing: Active and Passive, III, from Theory to Applications*. Artech House, Dedham, M.A.

Wigneron, J.-P., Calvert, J.-C. Kerr, Y.H., Chanzy, A. and Lopes, A., 1993. Microwave emission of vegetation, sensitivity to leaf characteristics. *IEEE Trans. Geosc. Remote Sens.*, **31**, 716–726.

Wigneron, J.-P., Calvet, J.-C. and Kerr, Y.H., 1996. Monitoring water interception by field crops follow passive microwave observations. *Agric. For. Meteorol.*, **80**, 122–194

Wigneron, J.-P., 1993. Modelisation de l'émission micro-onde d'un couvert végétal—Mise en relation de la mesure hyperfréquence passive avec les échanges énergetiques et hydriques d'une culture de soja. Doctorat de l'Université P. Sabatier, Toulouse.

Wilheit, T.T., 1978. Radiative transfer in a plane stratified dielectric. *IEEE Trans. Geosci. Remote Sens.*, **18**, 288–295.